Digital Elevation Models of Key West, Florida: Procedures, Data Sources and Analysis

Prepared for the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research by the NOAA National Geophysical Data Center (NGDC)
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1. Introduction

The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), has developed two bathymetric–topographic digital elevation models (DEMs) of Key West, Florida (Fig. 1). First, a 1/3 arc-second[1] DEM referenced to North American Vertical Datum of 1988 (NAVD 88) was developed and evaluated using diverse digital datasets available for the region (grid boundary and sources shown in Fig. 3). Then, a 1/3 arc-second conversion grid was created to represent the relationship between NAVD 88 and mean high water (MHW) vertical datums in the Key West region. Finally, a 1/3 arc-second MHW DEM was developed by combining the NAVD 88 DEM and the vertical datum conversion grid. The MHW DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by the Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the Key West DEMs.

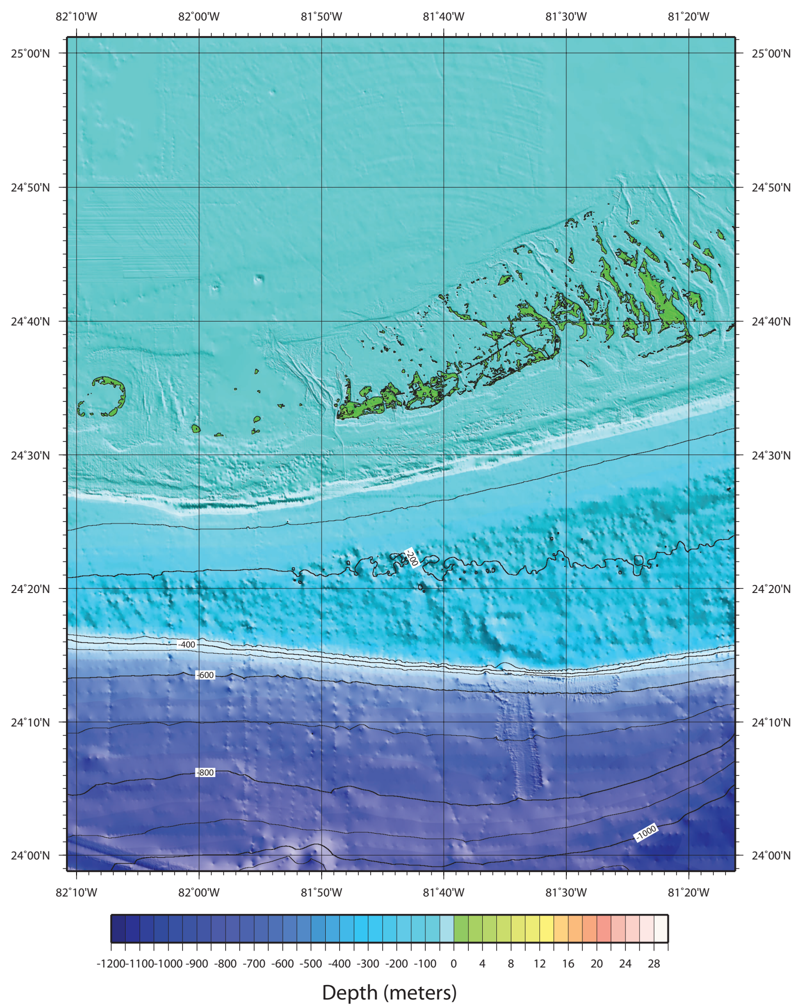

Figure 1. Shaded-relief image of the Key West NAVD 88 DEM. Contour interval is 100 meters for the bathymetry and 2 meters for the topography. Image is in Mercator projection.

1. The Key West DEMs are built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Key West, (24°33'19"N, 81°46'58"W) 1/3 arc-second of latitude is equivalent to 10.25 meters; 1/3 arc-second of longitude equals 9.38 meters.

2. Study Area

The Key West DEMs were constructed to meet PMEL specifications (Table 1), based on input requirements for the development of Reference Inundation Models (RIMs) and Standby Inundation Models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Centers use of SIFT to provide real-time tsunami forecasts in an operational environment. The DEMs encompass many of the lower Keys including Bahia Honda, Big Pine, Cudjow, Sugarloaf, and Boca Chica Keys east of Key West, and Boca Grande and Marquesas Keys west of Key West (Fig. 2). Key West is almost 130 miles southwest of Miami, Florida and slightly over 100 miles northeast of Havana, Cuba. The Keys formed from sediment collecting on limestone deposits that were raised above the sea surface through time.

The Keys low elevation makes them vulnerable to flooding hazards from hurricanes, sea level rise, and tsunamis. The worst recorded storm surge from a hurricane occurred in 2005 when Hurricane Wilma inundated Key West with three feet of water. No tsunami run-ups have been recorded in Key West. Although the tsunami threat is low, there is still a small risk with the Puerto Rico trench nearby.

Table 1. Specifications for the Key West DEMs

Grid Area	Key West, Florida
Coverage Area	81.27º to 82.18º W; 23.98º to 25.02º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	a) North American Vertical Datum of 1988 (NAVD 88) b) Mean High Water (MHW)
Vertical Units	Meters
Grid Spacing	1/3 arc-second
Grid Format	ESRI Arc ASCII raster grid

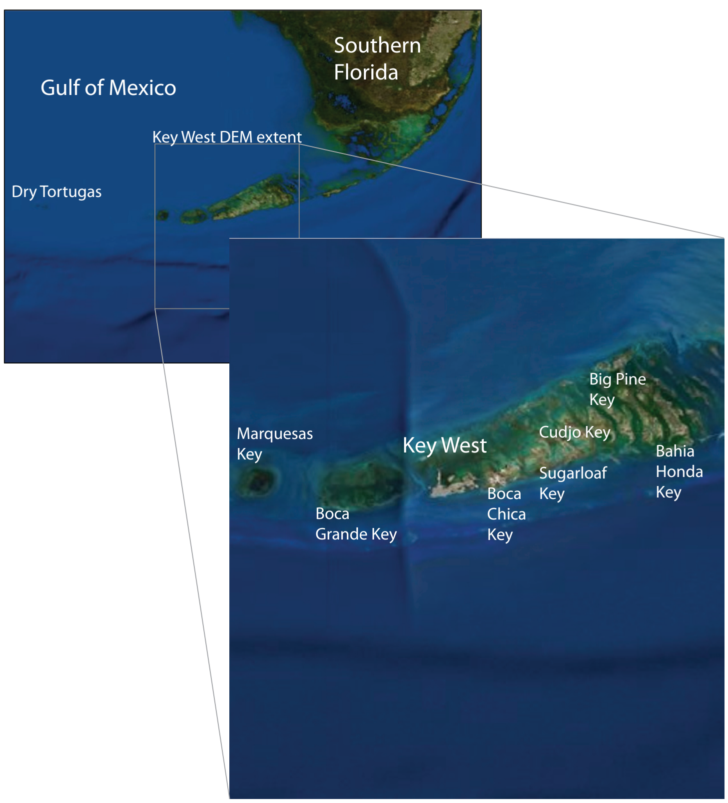

Figure 2. Map of the Key West region. ESRI Imagery in background.

3. SOURCE ELEVATION DATA

The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum 1983 (NAD 83)[2] and NAVD 88. Data were gathered in an area slightly larger (5%) than the DEM extents. This data 'buffer' ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

3.1 Data Sources and Processing

Coastline, bathymetric, and topographic digital datasets (Tables 2, 4, and 5; Fig.3) were obtained from the following U.S. federal and state agencies: NOAA's NGDC and Office of Coast Survey (OCS), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE), and South Florida Water Management District (SFWMD). Datasets were displayed either with Earth Systems Research Institute's (ESRI) *ArcGIS* or Applied Imagery's *Quick Terrain Modeler* software (*QT Modeler*) to assess data quality and manually edit datasets.

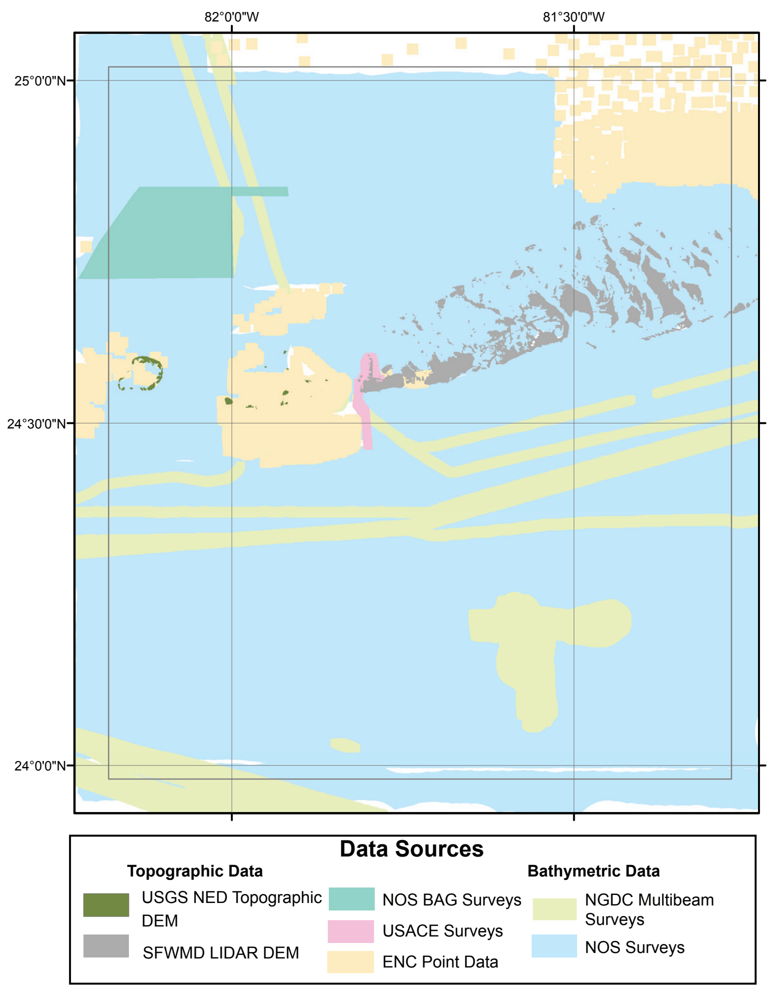

Figure 3. Data sources used in building the 1/3 arc-second Key West NAVD 88 DEM.

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (1984) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEM. Many GIS applications treat the two datums as identical and do not transform data between them. The error introduced by not converting between the datums is insignificant for NGDC purposes. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the waves passage across ocean basins. This DEM is identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geogprahic. At the scale of the DEM, WGS 84 and NAD 83 are identical and may be used interchangeably.

3.1.1 Coastline

Coastline datasets of the Key West region were obtained from two sources (Table 2; Fig. 4). The primary coastline dataset NGDC used was the zero contour line from the topographic contour shapefile derived by SFWMD from bare-earth topographic lidar data. This dataset provided a detailed NAVD 88 coastline for most of the Key West DEM coverage area. Two coastlines from NOAA's OCS were used for the islands west of Key West where no SWFWD lidar data were available to derive contours.

Table 2. Coastline datasets used in building the Key West NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*
OCS	2004-2006	ENC Coastline	1:30,000 - 1:80,000	WGS 84 geographic	MHW
SFWMD	2008	Composite vectorized contour lines from topographic lidar	3 meters	State Plane Coordinate System, US feet, Florida East Zone, NAD 83/HARN	NAVD 88 (feet)

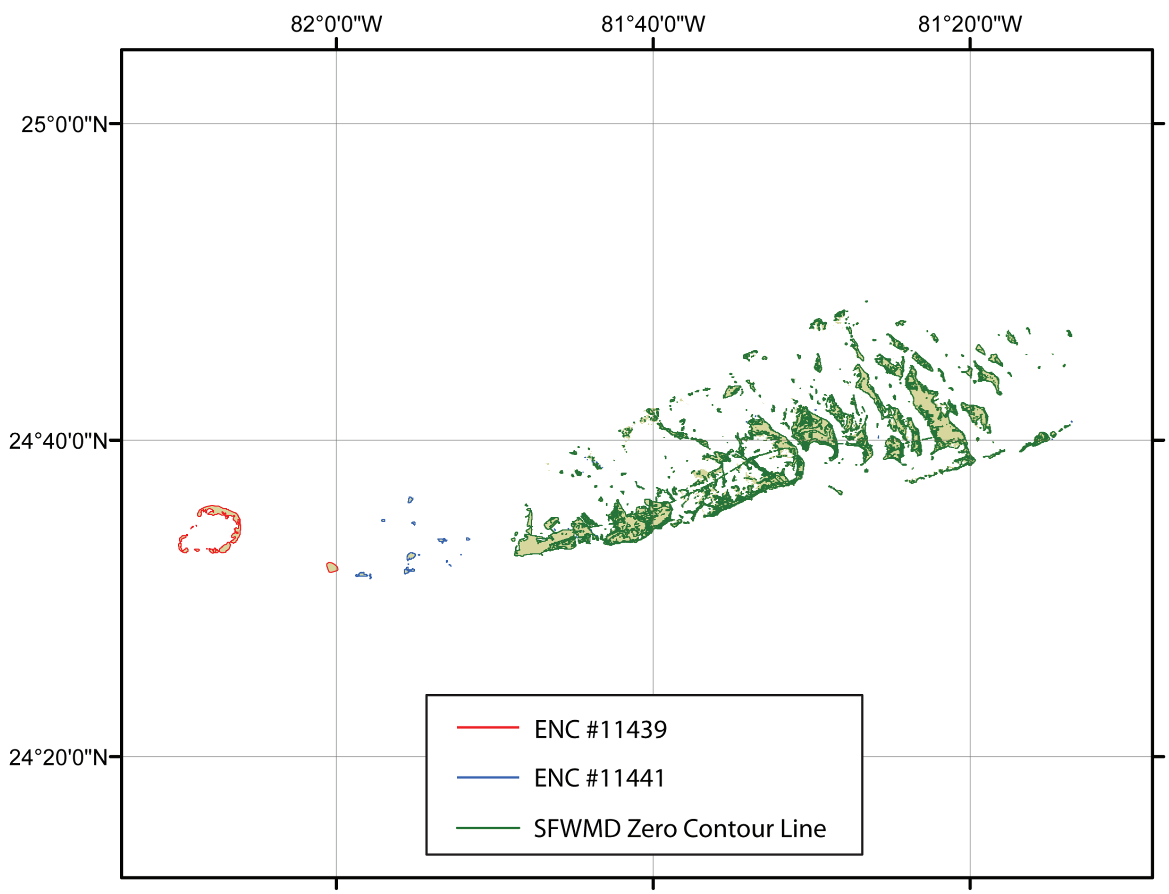

Figure 4. Coverage of coastline data sets used in building the Key West NAVD 88 DEM.

1) Office of Coast Survey extracted Electonic Navigational Chart coastlines

Eight ENCs were available in the Key West region (Table 4). They were downloaded from NOAA's OCS web site in S-57 format and included coastline data files referenced to MHW. The coastline shapefiles were extracted using Safe Software's *FME* data translation tool package and compared to large-scale georeferenced Raster Nautical Charts (RNCs). The coastlines from Chart #11439 and #11441 were merged together and used with the SFWMD zero contour line to create a continuous coastline of the Key West region.

Table 3. Available ENC/RNCs in the Key West Region.

Chart	*Title*	*Edition*	*Edition date*	*Format*	*Scale*
11434	Florida Keys Sombrero Key to Dry Tortugas	28	2008	RNC/ENC	1:180,000
11439	Sand Key to Rebecca Shoal	26	2004	RNC/ENC	1:80,000
11441	Key West Harbor and Approaches	41	2006	RNC/ENC	1:30,000
11442	Florida Keys Sombrero Key to Sand Key	35	2008	RNC/ENC	1:80,000
11445	Bahia Honda Key to Sugarloaf Key	30	2001	RNC/ENC	1:40,000
11446	Sugarloaf Key to Key West	32	2006	RNC/ENC	1:40,000
11447	Key West Harbor	37	2008	RNC/ENC	1:10,000
11448	Big Spanish Channel to Johnston Key	15	2006	RNC/ENC	1:40,000
11453	Grassy Key to Bahin Honda Key	17	2006	RNC/ENC	1:40,000

2) South Florida Water Management District Contour Lines

A shapefile of contour lines with 2 foot intervals, derived from the SFWMD lidar data, was available in the majority of the Key West DEM coverage region. The contours were vertically referenced to NAVD 88 and included elecation contours from 0 to -2 feet. The zero contour line was clipped from the other contours and merged with the OCS coastlines for use in building the Key West DEMs.

3.1.2 *Bathymetry*

Bathymetric datasets available in the Key West region include 48 National Ocean Servive (NOS) hydrographic surveys, three NOS high-resolution hydrographic surveys in Bathymetric Attributed Grid (BAG) format, nine multibeam surveys retrieved from the NGDC multibeam database, 21 USACE hydrographic surveys, and hydrographic soundings from ENCs (Table 4; Fig. 3). Hyperion-derived depth data were provided to NGDC by the Naval Research Lab but were not used to build the final DEM because the data lacked tidal constraint.

Table 4. Bathymetric datasets used in building the Key West NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/ Coordinate System*	*Original Vertical Datum*	*URL*
NGDC	1852 to 2003	NOS hydrographic survey soundings	Ranges from 5 meters to 2 kilometers (varies with scale of survey, depth, traffic and probability of obstructions)	Undetermined, NAD 27 geographic, NAD 83 geographic, NAD 83 UTM Zone 17	MLLW and MLW (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
NGDC	1995 to 2004	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
OCS	2002 to 2008	Extracted points from ENCs	1:10,000 and 1:80,000	WGS 84 geographic	MLLW	http://www.nauticalcharts.noaa.gov/mcd/enc/
USACE	2009	Hydrographic Channel/Harbor Surveys	5 - 30 meters	NAD 83 Florida State Plane, Eastern Zone, US Foot	MLLW	http://www.saj.usace.army.mil/Divisions/Operations/Branches/HydroSurvey/hydro.php

1) National Ocean Service hydrographic surveys

A total of 48 hydrographic surveys conducted between 1852 and 2003 were available for use in the development of the Key West DEMs. (Table A1). Surveys were extracted as xyz files using *GEODAS* from NGDC's online NOS Hydrographic database with a buffer 0.05 degrees (~5%) larger than the Key West DEM extent to support data interpolation along grid edges. The downloaded hydrographic survey data were vertically referenced to mean lower low water (MLLW) or mean low water (MLW) and horizontally referenced to NAD 83 geographic. Five surveys were not available from the on-line database. Two surveys, H10953 and H11658, were retrieved as GSF files from NGDC's archival system, vertically referenced to MLLW and horizontally referenced to NAD 83 UTM Zone 17. The other three were received from NOS in BAG format, vertically referenced to MLLW and horizontally referenced to NAD 83 UTM Zone 17 (Table A2).

Data point spacing for the NOS surveys varies by collection date. In general, earlier surveys had greater point spacing than more recent surveys. The data were displayed in ESRI's *ArcMap* and reviewed for digitizing errors against scanned original survey smooth sheets and edited as necessary. The surveys were also compared to various topographic and bathymetric data, the coastline, and OCS RNCs. Older sounding data were clipped to remove soundings that have been superseded by more recent surveys.

2) National Geophysical Data Center multibeam swath sonar surveys

Nine multibeam swath sonar surveys were available from the NGDC multibeam bathymetry database for use in the development of the Key West DEMs (Table A3). The data were horizontally referenced to WGS 84 geographic datum and were assumed to be vertically referenced to mean sea level (MSL) datum. The data were retrieved in xyz format to extents with a buffer of 0.05 degrees (5%) larger than the DEM extents at 3 arc-seconds using *MB-System*[3] and were viewed in *QT Modeler* for quality analysis. Editing was performed using *QT Modeler* to eliminate errors and where survey data overlapped. Most surveys were transits rather than dedicated seafloor surveys and were not used in the final DEM.

3) Office of Coast Survey Electronic Navigational Chart soundings

Nine ENCs were available from OCS in the Key West coverage area (see Table 3). The ENCs were downloaded from the OCS web site, and were horizontally referenced to NAD 83 geographic and vertically referenced to MLLW. The data were reviewed and compared to the coastline and corresponding RNCs. Points were only retained in the gaps between other datasets.

4) U.S. Army Corps of Engineers hydrographic surveys

Twenty-one USACE bathymetric surveys within the Key West DEM extent were downloaded from the USACE Jacksonville District web site in ascii xyz format (Table A4). The surveys were collected in 2009, and were referenced to NAD 83 Florida State Plane, Eastern Zone (feet) and MLLW datums. Surveys consist of numerous, parallel, across-channel profiles, spaced 10 to 100 meters apart, with point soundings 5 meters apart.

3. *MB-System* is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for *MB-System* is freely available (for free) by anonymous ftp (including "point and click" access through these web pages). A complete description is provided in web pages accessed through the web site. *MB-System* was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for *MB-System* development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994-1997), NOAA (2002-2004), and others. URL: http://www.ldeo.columbia.edu/res/pi/MB-System/ from *MB-System* web site.]

3.1.3 Topography

The topographic datasets used to build the Key West DEMs included: SFWMD lidar bare-earth DEM and USGS 1/3 National Elevation Dataset (NED) DEM (Table 5; Fig. 3). SFWMD lidar bare-earth DEM provided nearly full coverage of the Key West DEM area. NED DEM data were only used on the small islands west of Key West.

Table 5. Topographic datasets used in building the Key West NAVD 88 DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
SFWMD	2007 - 2008	Bare earth topographic DEM	3 meters	NAD 83 HARN State Plane Florida East (feet)	NAVD 88	http://www.sfwmd.gov/portal/page/portal/levelthree/gis
USGS	2009	Topographic DEM	10 meters	NAD 83 geographic	NAVD 88	http://seamless.usgs.gov/

1) South Florida Water Management District bare-earth lidar DEM

The SFWMD bare-earth lidar DEM was created from the 2007 Florida Division of Emergency Management (FDEM) lidar data, collected for the Statewide Coastal LiDAR project. The DEM was gridded at 10 ft (3 meters) and contained values down to -2 feet (-0.6 meters). The data were provided in a horizontal datum of NAD 83 State Plane Coordinate System Florida East Zone (feet) and vertical datum of NAVD 88. The assessed horizontal accuracy of this DEM was 1.15 meters and the vertical accuracy was 0.18 for open terrain and 0.36 meters in vegetated areas.

The DEM provided almost complete coverage of the Key West DEM area, and was used where available. Data values less than zero occurred in interior waterways and just off the coast due to flying at low tide and were retained for building the Key West DEMs. The DEM provided was already clipped to the -2 foot contour line and bridges and piers were not included.

2) USGS NED topographic DEM

The USGS NED topographic DEM provides complete 1/3 arc-second coverage of the Key West DEM coverage area, but the data were only used for the Keys west of Key West where the SFWMD lidar dataset did not exist. The data were in a horizontal datum of NAD 83 geographic and a vertical datum of NAVD 88, and were available for download as raster DEMs on the USGS web site. The bare earth elevations have a vertical accuracy of +/- 7 to 15 meters, respectively, but are most likely less than that in low elevation areas. The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys.

3.2 Establishing Common Datums

3.2.1 Horizontal datum transformations

Datasets used to build the Key West NAVD 88 DEM were originally referenced to WGS 84 geographic, NAD 83 geographic, NAD 27 geographic, NAD 83 UTM Zone 17 N, and NAD 83 Florida State Plane Coordinate Eastern Zone. The relationships and transformational equations between the geographic horizontal datums are well established. Transformations to WGS 84 geographic were accomplished using *FME* software or *GDAL's* transformation tool.

3.2.2 Vertical datum transformations

Datasets used to build the Key West NAVD 88 DEM were originally referenced to several vertical datums including MLLW, MLW, MSL, and NAVD 88. All datasets were transformed to NAVD 88 and converted to xyz using *VDatum*.

1) **Bathymetric data**

   All hydrographic surveys were transformed from MLLW, MLW, or MSL to NAVD 88 using *VDatum*.

2) **Topographic data**

   All topographic datasets used in building the Key West NAVD 88 DEM originated in NAVD 88 vertical datum. No further vertical datum transformations were required for these datasets.

3.2.3 Verifying transformations and consistency between datasets

After horizontal and vertical transformations were applied, datasets were checked for consistency and problems and errors were resolved before proceeding with subsequent gridding steps. All datasets were converted to xyz files using *GDAL* in preparation for gridding.

4. Structured Digital Elevation Model Development

4.1 Smoothing of bathymetric data

The NOS hydrographic survey data are generally sparse relative to the resolution of the 1/3 arc-second Key West DEMs. In order to reduce the effect of artifacts in the DEM by low-resolution NOS datasets, and to provide effective interpolation from the deep water into the coastal zone, a 1/3 arc-second-spacing 'pre-surface' bathymetric grid was generated using *Generic Mapping Tools (GMT)*[4]. The coastline elevation value was set to -1 meter to ensure a bathymetric surface below zero in areas where data are sparse or non-existent along the coast.

The point data were median-averaged using the *GMT* command 'blockmedian' to create a 1/3 arc-second grid 0.05 degrees (~5%) larger than the Key West DEM gridding region. The *GMT* command 'surface' was then used to apply a tight spline tension to interpolate elevations for cells without data values. The *GMT* grid created was converted into an ESRI Arc ASCII grid file, and clipped to the SWFMD lidar DEM and the ENC coastlines of the small islands west of Key West to eliminate data interpolation into land areas. The resulting surface was compared with original NOS soundings to ensure grid accuracy and then exported as an xyz file for use in the final gridding process.

4.2 Building the NAVD 88 DEM

MB-System was used to create the 1/3 arc-second Key West NAVD 88 DEM. The *MB-System* tool 'mbgrid' was used to apply a tight spline tension to the xyz data, and interpolate values for cells without data. The data hierarchy used in the 'mbgrid' gridding algorithm, as relative gridding weights, is listed in Table 6. The resulting binary grid was converted to an Arc ASCII grid using the *MB-System* tool 'mbm_grd2arc' to create the final 1/3 arc-second Key West NAVD 88 DEM. Figure 5 illustrates cells in the DEM that have interpolated values (shown as white) versus data contributing to the cell value (shown as gray).

Table 6. Data hierarchy used to assign gridding weight in *MB-System*.

Dataset	*Relative Gridding Weight*
SFWMD Lidar DEM	10
NOS hydrographic surveys	10
USACE hydrographic surveys	10
OCS ENC Soundings	10
SFWMD lidar DEM	1
NGDC multibeam	1
USGS NED DEM	1
Pre-surface bathymetric grid	0.1

4. *GMT* is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. *GMT* supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. *GMT* is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. URL: http://gmt.soest.hawaii.edu/ [Extracted from *GMT* web site.]

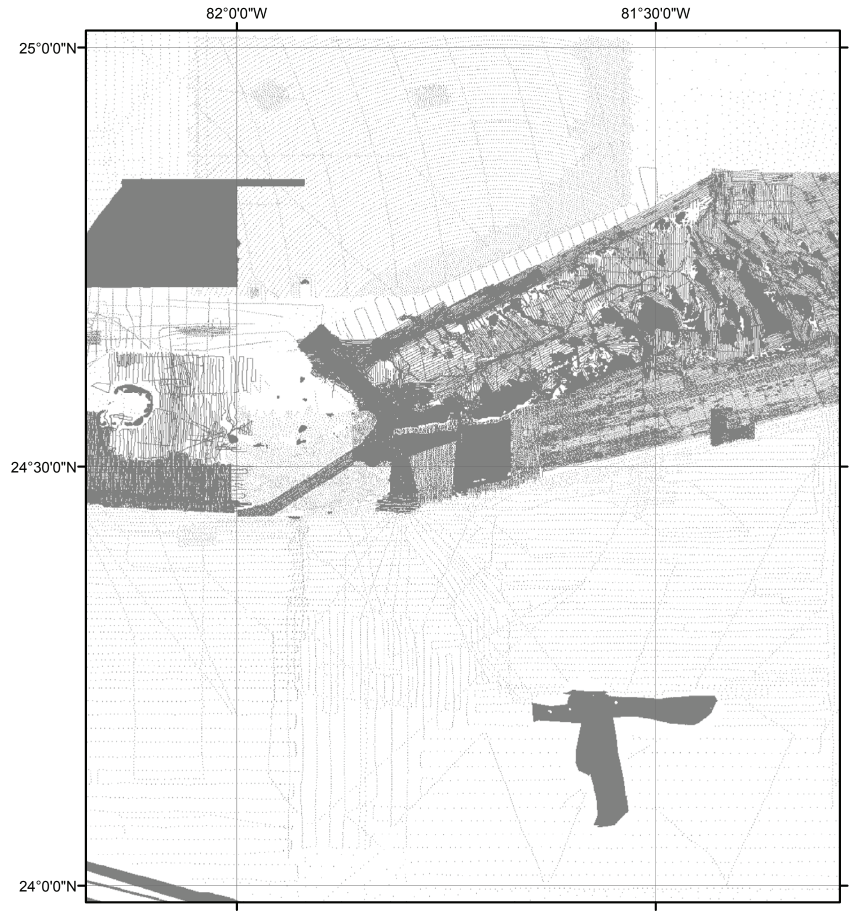

Figure 5. Data density of Key West; areas where source data were available are depicted in gray; areas where grid interpolation was necessary are depicted in white.

4.3 Building the MHW Structured DEM

The MHW DEM was created by adding a 'NAVD 88 to MHW' conversion grid to the NAVD 88 DEM.

4.3.1 Developing the conversion grid

Using extents slightly larger (~5%) than the Key West NAVD 88 DEM, an intial xyz file was created that contained the coordinates of the four bounding vertices and midpoint of the larger extents. The elevation value at each of the points was set to zero. The *GMT* command 'surface' applied a tension spline to interpolate cell values making a zero-value 3 arc-second grid. This zero-grid was then converted to an intermediate xyz file using the *GMT* command 'grd2xyz'. Conversion values from NAVD 88 to MHW at each xyz point were generated using *VDatum* and the null values were removed.

The median-averaged xyz file was then interpolated with the *GMT* command 'surface' to create the 1/3 arc-second 'NAVD 88 to MHW' conversion grid with the extents of the Key West project area. NGDC then used the *GMT* command 'surface' to interpolate values that represented the differences between the two datums onshore to the DEM extents (Fig. 6).

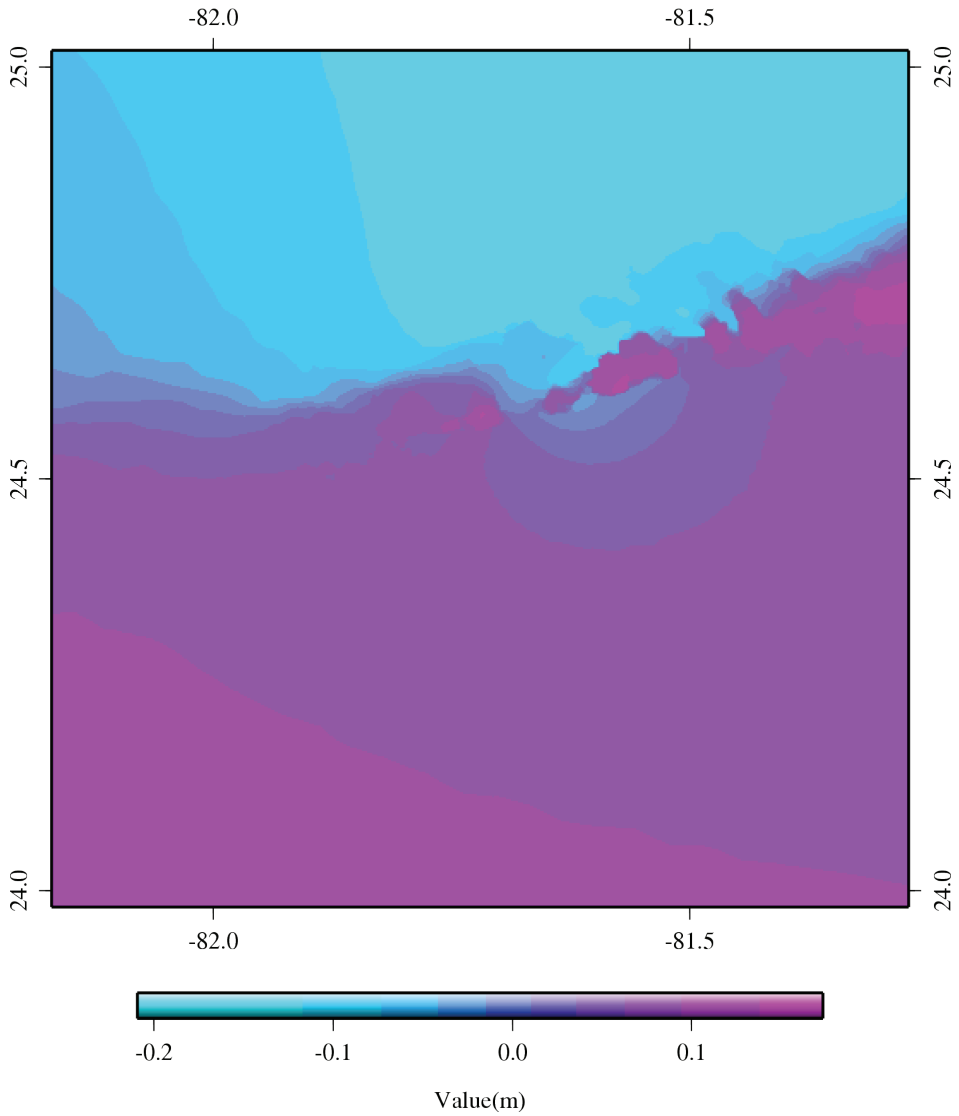

Figure 6. Elevation conversion values of the 'NAVD 88 to MHW' conversion grid derived from VDatum. Values equal difference between NAVD 88 and MHW.

4.3.2 Assessing accuracy of conversion grid

The 'NAVD 88 to MHW' conversion grid was assessed using the NOS survey data. For testing of this methodology, the NOS hydrographic survey data were transformed from MLW and MLLW to NAVD 88 using *VDatum*. The resulting xyz files were filtered to remove any null values and then were merged together to form a single xyz file of the NOS hydrographic survey data with a vertical datum of NAVD 88. A second xyz file of NOS data was created with a vertical datum of MHW using the same method. Elevation differences between the MHW and NAVD 88 xyz files were computed.

To verify the conversion grid methodology, the difference xyz file was used to generate a histogram using *Gnuplot*[5] to evaluate the perfomance of the 1/3 arc-second conversion grid by comparing the 'NAVD 88 to MHW' grid to the combined difference xyz files from the *VDatum* project area. Errors in the vertical datum conversion method will reside for the most part in the 'NAVD 88 to MHW' conversion grid, as the topographic data are already referenced to NAVD 88. Errors in the source datasets will require rebuilding just the NAVD 88 DEM.

5. *Gnuplot* is an open-source command-driven interactive function plotting program. It can be used to plot functions and data points in both two- and three-dimensional plots in many different formats. It is designed primarily for the visual display of scientific data.

4.3.3 Creating the MHW structured DEM

Once the NAVD 88 DEM was completed and assessed for errors, the conversion grid was added to the NAVD 88 DEM using the GMT command 'grdmath'. The resulting MHW DEM was reviewed and assessed using RNCs, USGS topographic maps, and ESRI *World 2D* imagery.

4.4 Quality Assessment of the DEMs

4.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Key West DEMs is dependent upon the datasets used to determine corresponding DEM cell values and the cell size of the DEM. The horizontal accuracy is 10 meters for the topographic data. Bathymetric features are resolved only to within a few tens of meters in deep-water areas. Shallow, near-coastal regions have an accuracy approaching that of sub-aerial topographic features. Positional accuracy is limited by the sparseness of deep-water soundings, potentially large positional uncertainty of pre-satellite navigated (e.g., GPS) NOS hydrographic surveys, and by the morphologic change that occurs in this dynamic region.

4.4.2 Vertical accuracy

Vertical accuracy of the Key West DEMs are also highly dependent upon the source datasets contributing to DEM cell values. The SFWMD topographic lidar DEM has an estimated vertical accuracy of 0.18 m in open terrain and 0.36 m in highly vegetated areas. USGS NED DEM has a stated vertical accuracy of 7 to 15 meters but we find it to be much less for low lying areas like Key West. Bathymetric areas have an estimated accuracy of between 0.1 m and 5% of water depth. Those values were derived from the wide range of input data sounding measurements from the early 20th century to recent, GPS-navigated sonar surveys. Gridding interpolation to determine bathymetric values between sparse, poorly located NOS soundings degrades the vertical accuracy of elevations.

4.4.3 Slope map and 3-D perspectives

ESRI *ArcCatalog* was used to generate a slope grid from the Key West NAVD 88 DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 7). The DEM was transformed to UTM Zone 17 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Three-dimensional viewing of the UTM-transformed DEM was accomplished using ESRI *ArcScene.* Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM. Figure 8 shows a perspective view image of the 1/3 arc-second Key West NAVD 88 DEM in its final version.

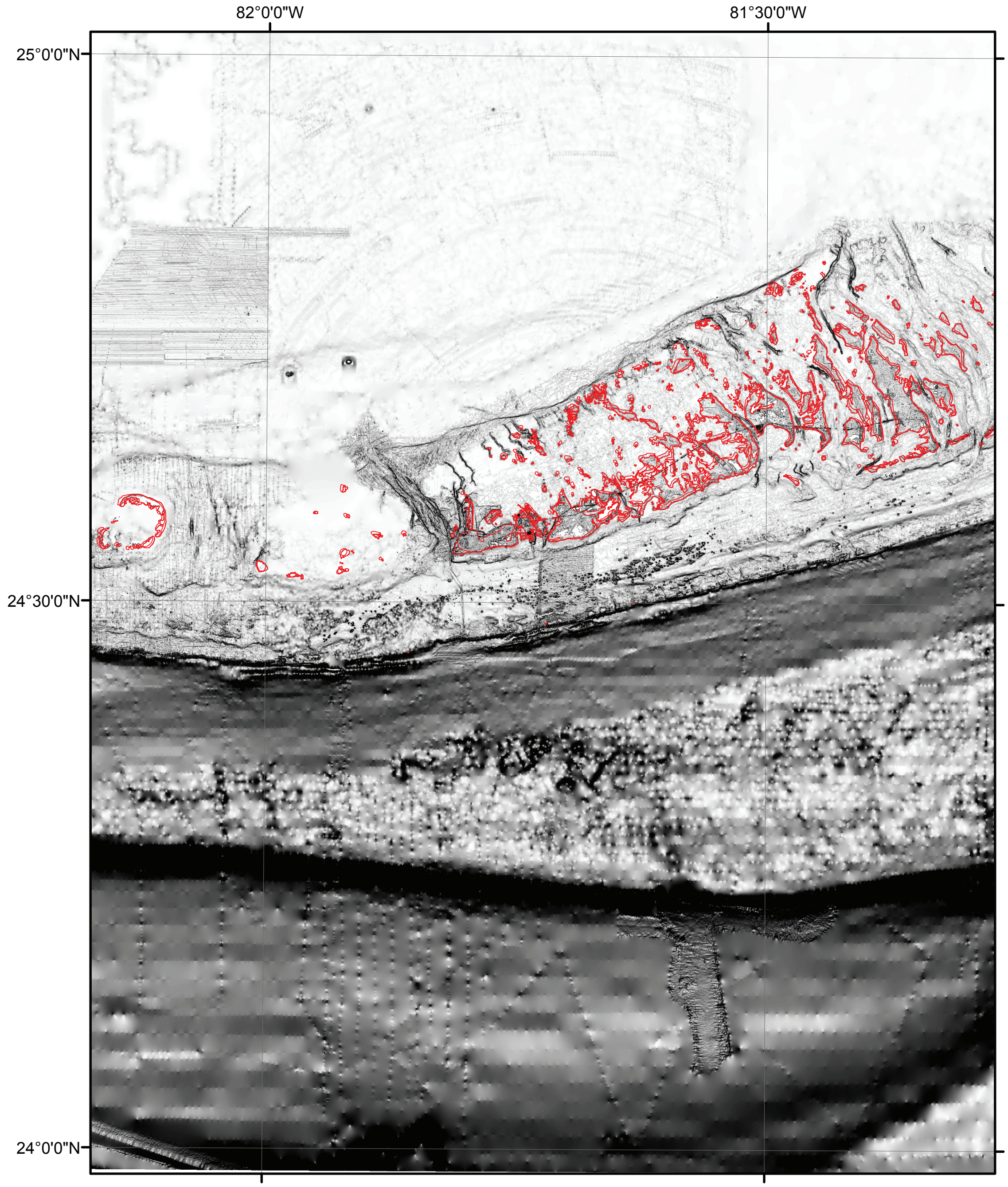

Figure 7. Slope map of the Key West NAVD 88 DEM. Flat-lying slopes are white; dark shading denotes steep slopes. Final coastline in red.

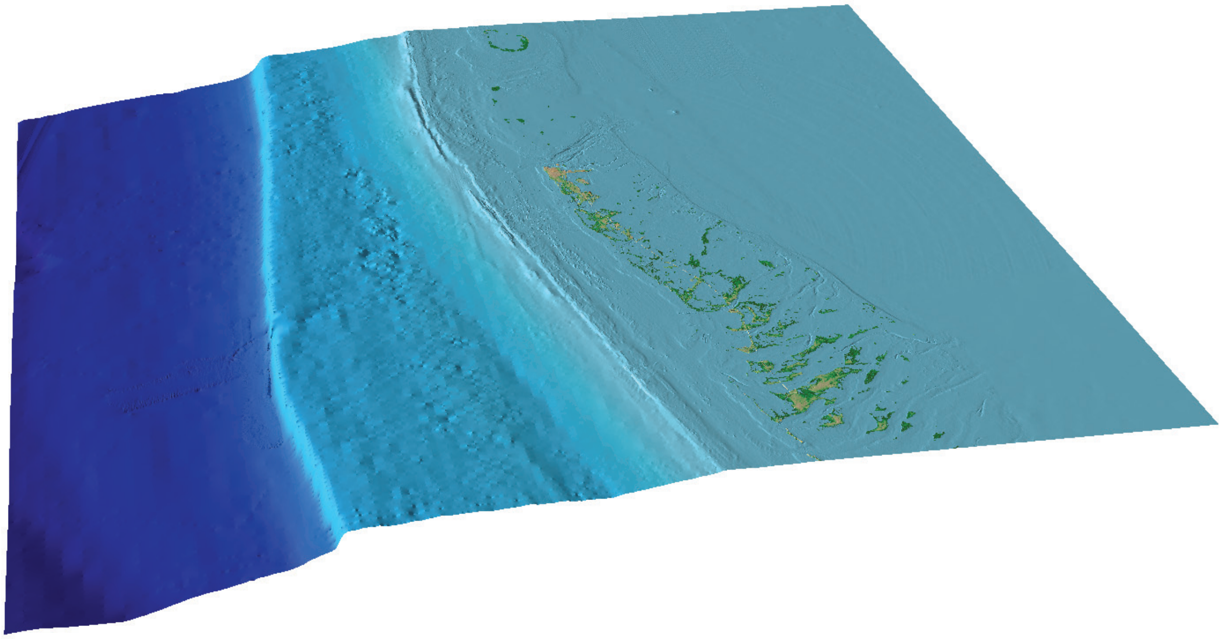

Figure 8. Perspective view from the southeast of the Key West NAVD 88 DEM. Five times vertical exaggeration.

4.4.4 Comparison of the NAVD 88 structured DEM with source data files

To ensure grid accuracy, the Key West NAVD 88 DEM was compared to source data files. All bathymetric and topographic source data were compared to the Key West NAVD 88 DEM using *Python*, *GDAL*, and *Gnuplot*. Histograms of the differences between individual datasets and the Key West DEM mostly cluster around zero.

4.4.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of 494 NOAA National Geodetic Survey (NGS) geodetic monuments (Fig. 9) were extracted from online shapefiles of NGS Geodetic monument datasheets (http://www.ngs.noaa.gov/), which give monument positions in NAD 83 (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Monuments with conditions noted as 'GOOD' or 'MONUMENTED' were only included in the analysis. Monument elevations were compared with elevations of the Key West NAVD 88 DEM. Differences between the Key West NAVD 88 DEM and the NGS geodetic monument elevations range from -4 to 12 meters, with the majority of them being with +/-1 meter (Fig. 10). Negative values indicate that the monument elevation is less than the DEM elevation. After examination, it was determined that those monuments with the largest deviations do not represent ground surface as they are located on top of a light house, on a bridge, or at the apex of other structures.

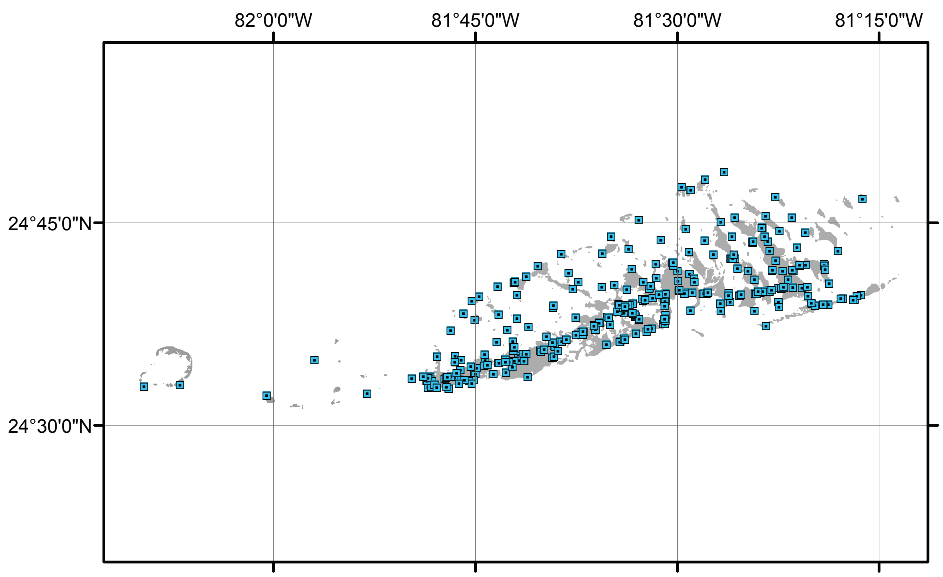

Figure 9. Location of NGS geodetic monuments in the Key West region.

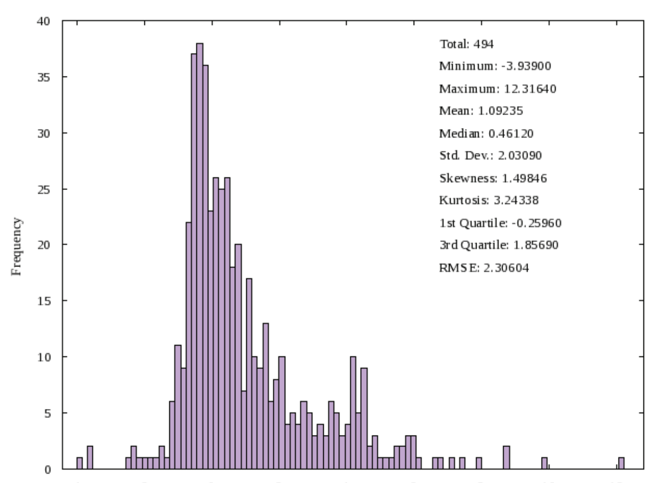

Figure 10. Histogram of the differences between NGS geodetic monument elevations and the Key West NAVD 88 DEM.

5. SUMMARY AND CONCLUSIONS

Two 1/3 arc-second bathymetric–topographic square-cell DEMs of the Key West region, one vertically referenced to NAVD 88 and the other to MHW, were developed for the purpose of modeling tsunami inundation and to support other coastal management activities. The best available digital data from U.S. federal, state, and local agencies were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using ESRI *ArcGIS*, *FME*, *GMT*, *MB-System*, *QT Modeler*, *GDAL*, *Proj4*, and *Gnunplot* software. *VDatum* was utilized throughout the development to transform data to common vertical datums. Futhermore, NGDC developed a conversion grid derived from *VDatum* that transformed source data to NAVD 88 and the Key West NAVD 88 DEM to MHW.

Recommendations to improve the Key West DEMs, based on NGDC's research and analysis, include:

- Conduct high-resolution shallow-water bathymetric multibeam surveys to replace late 18th and early 19th century surveys.
- Conduct bathymetric lidar surveys of the near-shore regions to allow for a smooth transition from the bathymetric data to the topographic data.
- Conduct high-resolution deep-water bathymetric multibeam surveys.

6. ACKNOWLEDGMENTS

The developement of the Key West DEMs was funded by the NOAA Pacific Marine Environmental Laboratory. The authors thank Nazila Merati, Marie Eble, and Vasily Titov (PMEL).

7. REFERENCES

Nautical Chart #11434 (RNC), 28th Edition, 2008. Florida Keys Sombrero Key to Dry Tortugas. Scale 1:180,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11439 (RNC), 26th Edition, 2004. Sand Key to Rebecca Shoal. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11441 (RNC), 41st Edition, 2006. Key West Harbor and Approaches. Scale 1:30,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11442 (RNC), 35th Edition, 2008. Florida Keys Sombrero Key to Sand Key. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11445 (RNC), 30th Edition, 2001. Bahia Honda Key to Sugarloaf Key. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11446 (RNC), 32nd Edition, 2006. Sugarloaf Key to Key West. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11447 (RNC), 37th Edition, 2008. Key West Harbor. Scale 1:10,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11448 (RNC), 15th Edition, 2006. Big Spanish Channel to Johnston Key. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Nautical Chart #11453 (RNC), 17th Edition, 2006. Grassy Key to Bahia Honda Key. Scale 1:40,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

8. Data Processing Software

ArcGIS v. 10.0 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/.

FME 2010 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/.

GDAL v. 1.7.1 – Geographic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://gdal.org/.

GEODAS v. 5 – Geophysical Data System, freeware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/.

GMT v. 4.3.4 – Generic Mapping Tools, freeware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/.

Gnunplot v. 4.2, free software developed and maintained by Thomas Williams, Colin Kelley, Russell Lang, Dave Kotz, John Campbell, Gershon Elber, Alexander Woo, http://www.gnuplot.info/.

MB-System v. 5.1.0 – software developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/.

Proj4 v. 4.7.0, free software developed by Gerald Evenden and maintained by Frank Warmerdam, http://trac.osgeo.org/proj/.

Python v. 2.4.3, Python is a remarkable pwerful dynamic programming lanuage that is used in a wide variety of application domains. Python is free software, http://python.org/.

Quick Terrain Modeler v. 7.0.0 – LiDAR processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.

VDatum Transformation Tool, Florida - Florida - South Florida, Naples to Fort Lauderdale FL, and Florida Bay V. 01, – developed and maintained by NOAA's National Geodetic Survey (NGS), Office of Coast Survey (OCS), and Center for Operational Oceanographic Products and Services (CO-OPS), http://vdatum.noaa.gov/

Appendix A. Bathymetric Surveys

Table A1. NOS Hydrographic surveys available in the Key West DEM region.

NOS Survey ID	*Year of Survey*	*Survey Scale*	*Original Horizontal Datum*	*Original Vertical Datum*
D00126	1998	10,000	NAD 83 geographic	MLLW
D00127*	1998	10,000	NAD 83 geographic	MLLW
F00283*	1986	5,000	NAD 27 geographic	MLLW
F00342*	1982	10,000	NAD 27 geographic	MLLW
H00359*	1852	20,000	Undetermined	MLW
H01076	1871	80,000	Undetermined	MLW
H01825	1888	unknown	Undetermined	MLW
H01828	1888	40,000	Undetermined	MLW
H03299	1911	40,000	Undetermined	MLW
H03301	1911	20,000	Undetermined	MLW
H03724	1915	20,000	Undetermined	MLW
H04166	1920	15,000	Undetermined	MLW
H05908	1935	10,000	NAD 27 geographic	MLW
H05909	1935	10,000	NAD 27 geographic	MLW
H05922	1935	10,000	NAD 27 geographic	MLW
H05923	1935	10,000	NAD 27 geographic	MLW
H05924	1935	10,000	NAD 27 geographic	MLW
H05925	1935	10,000	NAD 27 geographic	MLW
H05934	1937	10,000	NAD 27 geographic	MLW
H05935	1935	10,000	NAD 27 geographic	MLW
H06137	1936	20,000	NAD 27 geographic	MLW
H06158	1936	20,000	NAD 27 geographic	MLW
H06318	1938	20,000	NAD 27 geographic	MLW
H06323	1938	20,000	NAD 27 geographic	MLW
H06324	1939	20,000	NAD 27 geographic	MLW
H06325	1939	20,000	NAD 27 geographic	MLW
H06326	1939	20,000	NAD 27 geographic	MLW
H07932	1951	20,000	NAD 27 geographic	MLW
H07933	1954	80,000	NAD 27 geographic	MLW
H08011	1952	80,000	NAD 27 geographic	MLW
H08017	1954	200,000	NAD 27 geographic	MLW
H08295*	1956	10,000	NAD 27 geographic	MLW
H08305	1956	10,000	NAD 27 geographic	MLW
H08570*	1960	200,000	NAD 27 geographic	MLW
H08626	1961	40,000	NAD 27 geographic	MLW
H08628	1961	80,000	NAD 27 geographic	MLW
H08762	1963	20,000	NAD 27 geographic	MLW
H08763	1963	10,000	NAD 27 geographic	MLW
H10086	1984	5,000	NAD 27 geographic	MLW
H10120	1983	5,000	NAD 27 geographic	MLW
H10125	1984	5,000	NAD 27 geographic	MLW
H10187	1984	5,000	NAD 27 geographic	MLW
H10221	1986	10,000	NAD 27 geographic	MLLW

NOS Survey ID	Year of Survey	Survey Scale	Original Horizontal Datum	Original Vertical Datum
H10954	2000	20,000	NAD 83 geographic	MLLW
H10955	2000	10,000	NAD 83 geographic	MLLW
H10956	2001	5,000	NAD 83 geographic	MLLW
H10953	2000	20,000	NAD 83, UTM Zone 17	MLLW
H11658	2007	5,000	NAD 83, UTM Zone 17	MLLW

*indicates data were not used due to poor quality or overlapped by more recent survey

Table A2. Digital NOS high-resolution hydrographic surveys in BAG format in the Key West DEM region.

NOS Survey ID	Year of Survey	Survey Scale	Original Horizontal Datum	Original Vertical Datum
H12191	2010	40,000	NAD 83, UTM Zone 17	MLLW
H12193	2010	40,000	NAD 83, UTM Zone 17	MLLW
H12198	2010	40,000	NAD 83, UTM Zone 17	MLLW

Table A3. Multibeam swath sonar surveys available in the Key West DEM region.

Survey ID	Date	Institution	Ship
EW0302	2003	Columbia University, Lamont-Doherty Earth Observatory (CU/LDEO)	Maurice Ewing
EW0403	2004	CU/LDEO	Maurice Ewing
EW9501	1995	CU/LDEO	Maurice Ewing
EW9609	1996	CU/LDEO	Maurice Ewing
EW9701a	1997	CU/LDEO	Maurice Ewing
KN166L02	2002	Woods Hole Oceanographic Institution (WHOI)	Knorr
KN166L04	2004	WHOI	Knorr
USF2000	2000	University of South Florida (USF)	Bellows
USF2002FLA	2002	USF	Bellows

Table A4. USACE hydrographic surveys used in building the Key West DEM.

Survey	Spatial Resolution
x_09-144cta_LL	~ 20 - 100 m profile spacing; ~5 m point spacing
x_09-144ctb_LL	~ 20 - 50 m profile spacing; ~5 m point spacing
x_09-144ctc_xs	~ 30 m profile spacing; ~ 5 m point spacing
x_09-144gb1_LL	~ 15 m profile spacing; ~ m point spacing
x_09-144gb2_LL	~ 15 m profile spacing; ~ 5 m point spacing
x_09-144gb3_LL	~ 10 m profile spacing; ~ 5 m point spacing
x_09-144gb4_LL	~ 15 m profile spacing; ~ 5 m point spacing
x_09-144gb5_LL	~ 15 m profile spacing; ~ 5 m point spacing
x_09-144gb6_LL	~ 15 m profile spacing; ~ 5 m point spacing
x_09-144gb8_LL	Single profile; ~ 5 m point spacing
x_09-144gb9_LL	Single profile; ~ 5 m point spacing
x_09-144gbtb_LL	Single profile; ~ 5 m point spacing
x_09-144kwb1_xs	~ 15 - 30 m profile spacing; ~ 5 m point spacing
x_09-144kwb2_xs	~ 15 - 30 m profile spacing; ~ 5 m point spacing
x_09-144kwb3_LL	~ 15 - 20 m profile spacing; ~ 5 m point spacing